Electrical Generation Using a Vertical-Axis Wind Turbine

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ABSTRACT

TRADITIONALLY, windmills have been of the propeller or multiblade types, both of which have their rotational axis parallel to the flow of the wind. A vertical-axis wind turbine has its rotational axis perpendicular to the flow of wind and requires no orientation to keep the rotor in the windstream. The vertical-axis wind turbine operates on the same principle as any airfoil by producing lift and drag forces.

A newly designed 100-kW vertical-axis wind turbine has been operated for one year at the USDA Conservation and Production Research Laboratory, Bushland, Texas. The turbine has an induction generator and supplies power to a sprinkler irrigation system with excess power being sold to the electric utility. The turbine begins producing electric power at 5.5 m/s windspeed and reaches its rated output of 100 kW at 14 m/s. The unit has obtained a peak efficiency of 43% at a windspeed of 7 m/s or 73% of theoretical maximum. Using 17 years of windspeed data from the National Weather Service, the annual energy output is estimated at 200,000 kWh.

The unit has experienced several operational problems during its initial testing. Guy cables were enlarged to provide greater stiffness at the top of the turbine to reduce blade stress levels. Also, the main contactor shorted and the brake system required a complete redesign and modification. The turbine was capable of operation about 60% of the time.

INTRODUCTION

Windpower has been used for many years to generate small amounts of electricity for rural and remote areas. Traditionally, windmills have been of the propeller or multiblade types both of which have their rotational axis parallel to the flow of the wind. In 1925, a Frenchman named G. J. M. Darrieus proposed a new type of wind turbine, which had its rotating shaft perpendicular to the flow of the wind. In recent years, similar designs have been developed and refined by the National Research Council of Canada and Sandia Laboratories. This discussion of vertical-axis wind turbines will be limited to the Darrieus types and will not address the similar gyromill, Savonius, and other types.

The vertial-axis wind turbine, of the Darrieus type, consists of airfoil shaped blades mounted in a curved shape about a vertical axis (Fig. 1). The curvature of the blades is the shape that a flexible cable of uniform cross section and weight would assume if spun about a vertical axis. This blade shape is referred to as troposkien. Blades rotating in a troposkien shape normally do not bend and the stress is pure tension.

The major advantage that the vertical-axis wind turbine has over conventional propeller-type wind turbines is that they do not have to be turned into the windstream as the wind direction changes. This reduces the design complexity by eliminating a yaw control and reduces the gyroforce on the rotor. Another advantage of vertical-axis wind turbines is that gearboxes, brakes,

Fig. 1—100-kW vertical-axis wind turbine with centerline rotor height of 25 m and a equatorial diameter of 17 m.

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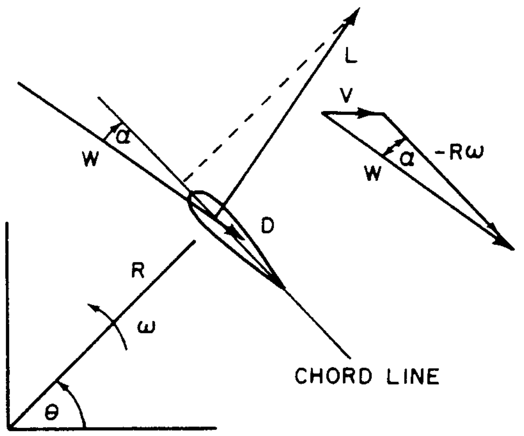

Fig. 2—Aerodynamic forces acting on a rotating airfoil. L = lift, D = drag force, Rω = absolute blade velocity, α = angle of attack, and θ = blade position angle.

generators, and other components can be placed at ground level. Fabrication and maintenance costs are reduced because heavy, high maintenance items are easily accessible. Also, the vertical-axis design uses a simple low cost tower.

Because of the orientation of the rotor blades and low solidity (rotor surface area divided by that rotor's swept area), the system stalls at low rotational speeds, thus impeding starting of the turbine. To overcome this starting problem, an auxiliary starting system is used which normally is the induction generator operated as an electrical motor.

Because vertical-axis wind turbines require a guy-wire support system to hold the top erect, large land areas are often required. Normally the units are erected as close to the ground as feasible, thus potentially reducing the output of the turbine. Normally an economic compromise is reached between turbine height, land area required, and energy produced.

OPERATING PRINCIPLES

The operational principle of the vertical-axis turbine is analogous to the aerodynamics of an airfoil used on aircraft. As wind moves over the airfoil, forces are exerted on the airfoil. These forces are usually called lift and drag where the drag force is parallel to the wind and the lift force is perpendicular to the drag force. The angle between the chord line and the wind direction is called the angle of attack. When the airfoil is symmetrical as shown in Fig. 2, the chord line corresponds to the centerline of the cross section of the airfoil (Blackwell, 1974). Stall occurs if the angle of attack is high enough to cause the flow to separate from the airfoil. For optimum aerodynamic performance, the stall condition should be avoided.

The forces that cause rotation are determined by projecting the lift force (L) and the drag force (D) onto the direction of the chord line of the airfoil (Fig. 2). As long as the chordwise lift force is greater than the chordwise drag force, the driving torque will be positive, thus causing rotation. The amount of lift produced by the airfoil continually changes as the airfoil rotates around its path. But if the rotational speed is much higher than the windspeed, at a tip speed ratio of 5 or 6, little power loss is encountered and the rotor operates successfully (Park, 1981).

DESCRIPTION OF 100-kW WIND TURBINE

The wind turbine used in this experiment was built for the Department of Energy. Sandia Laboratories by Alcoa in 1980. Table 1 (Alcoa, 1983) contains several of the important specifications for this unit. Four units were originally built with Unit No. 2 being installed at the USDA Conservation and Production Research Laboratory at Bushland, Texas. Installation was completed March 1981, and certification testing completed in August 1981. Fig. 1 is a photograph of the test unit. The two blades are extruded aluminum with a 610-mm chord with 4 internal ribs for bracing. The airfoil is a NACA 0015; a high lift, low drag section frequently used for helicopter blades.

The turbine top stands 29 m above the ground surface and is supported by 3 steel guy cables each 41 mm in diameter. The foundation and guy anchors are reinforced concrete piers with bell ends.

The electric generator is an induction motor/generator rated at 112 kW operating at slightly above 1800 r/min. The generator operates on a 3-phase, 60-Hz, 480-V AC electric line of the type commonly used for irrigation service. The induction motor/generator operates as a generator when operated above its normal synchronous speed; therefore, the control system is designed to automatically disconnect the generator from the utility power when rotational speed drops below 1800 r/min. Also, the control system does not connect the generator

TABLE 1. SPECIFICATION OF 100-kW DARRIEUS VERTICAL -AXIS WIND TURBINE

Rotor	
Number of blades	2
Axial height	25.3 m
Diameter (at centering)	16.8 m
Speed	48.1 r/min
Swept area	270 m^2
Blade	
Length (total)	30.8
Airfoil	NACA 0015
Chord	609.6 mm
Thickness	92.40 mm
Material	extruded aluminum
Torque Tube	
Material	steel
Diameter	0.91 m
Tower	
Type	platform
Height	2.7 m
Transmission	
Type	Gear increaser
Ratio	37.1
Input speed	48.1 r/min
Output speed	1825 r/min
Generator/Motor	
Type	Induction
Power	125 kW
Voltage	460 V, 3-phase
Frequency	60 Hz
Performance	
Rated power	100 kW at 15 m/s*
Start-up	5.5 m/s*
Cut-in	5.5 m/s*
Cut-out	20.1 m/s*
Maximum design	58.1 m/s*

* Windspeed measured at 10 m.

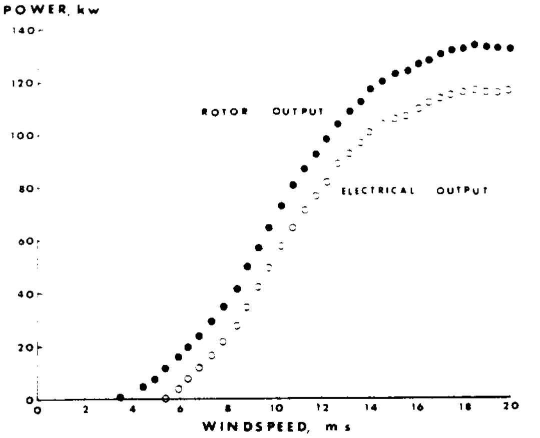

Fig. 3—Electrical power and rotor power from a 17-m vertical-axis wind turbine with induction generator at Bushland, Texas.

until windspeed in high enough to maintain the turbine above synchronous speed. The unit also disconnects from the utility line in case of a power outage, thus protecting electric utility repair crews.

PERFORMANCE DATA

During the initial testing the turbine was primarily operated in a manual mode and detailed stress analysis and rotor dynamics data collected. After approximately 6 months of operation, larger guy cables were installed to reduce the stress levels in the blade-end sections and joints. These enlarged cables reduced stress by almost 25% and automatic operation of the turbine began. A start-up windspeed of 5.5 m/s and a cut-out or shutdown windspeed of 20 m/s was selected. The turbine has operated for over 2,600 h and produced 68,000 kWh during its first year. The turbine has had several problems and two major design changes, which will be discussed in a later section on operational experience.

The power curve for the 100-kW wind turbine is similar to most vertical-axis units but does not exhibit reduced power at high windspeeds (Fig. 3). The power produced by the rotor was measured by a torque sensor before entering the transmission. The electrical output shown in Fig. 3 represents the usable power supplied at the main disconnect of the wind turbine system. The power losses in the transmission and induction generator averaged about 15% over the entire range and were uniform at about 12% when power was above 50 kW.

The efficiency of the wind turbine system is shown in Fig. 4. The power coefficient or efficiency is the ratio of actual power extracted to the theoretical power in the windstream. The theoretical maximum efficiency is 0.593 and is known as the Betz coefficient (Eldridge, 1980). The Betz coefficient represents the ideal efficiency for lift type wind turbines. The 100-kW unit reached a peak efficiency of 0.43 at a tip speed ratio of 6. This efficiency is slightly higher than most two- or three-blade propeller units and is almost twice as high as previously tested vertical-axis units. One reason for its high efficiency is the clean aerodynamic shape of the unit and an optimum rotational speed. The curve in Fig. 4 also illustrates the need for modifying the airfoil to allow for a flatter efficiency curve so that the unit would operate at a higher efficiency over a broader range of windspeeds.

The annual power output was estimated by using 17

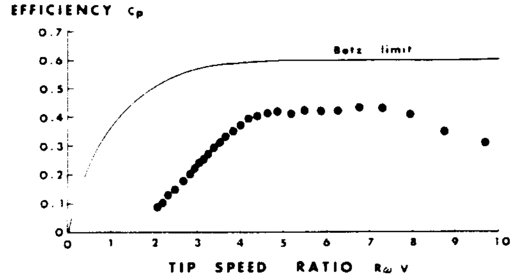

Fig. 4—Efficiency or power coefficient (cp), for a 17-m vertical-axis wind turbine, as a function of the tip speed ratio (Rω/v) as compared to the theoretical maximum as defined by Betz.

years of wind data from the local National Weather Service Office. An average windspeed histogram for each month was prepared from the windspeed data. The power output of the wind turbine for each one-half m/s windspeed increment was matched to the hours per month of the same increment to calculate the energy output. The sum of the increments yielded the potential monthly output as shown in Fig. 5.

March and April are the best months, providing 21,700 kWh of electricity during each month, while August is the lowest at 11,600 kWh. The yearly total is 199,200 kWh. These data assume that the turbine operates 100% of the time and provide no corrections for changes in air density. Using the same data and correcting them to standard density (sea level), the power would be increased to 244,000 kWh or about a 22% increase. Based on my operational experience with wind turbines in allowing time for maintenance, repairs, and general downtime, I feel the annual energy level would be about 150,000 kWh for the Bushland area.

OPERATING EXPERIENCES

The wind turbine has been operated for almost 18 months, the first 6 months in a certification test mode and then in an automatic operation mode. During the certification testing and after about 200 h of operation some of the torque tube bolts were loose. After close examination and retorquing, the self-locking nuts with crimped wire were found to be inadequate. All bolts in the torque tube connections and blade-to-torque tube connections were replaced with self-locking nuts containing nylon inserts.

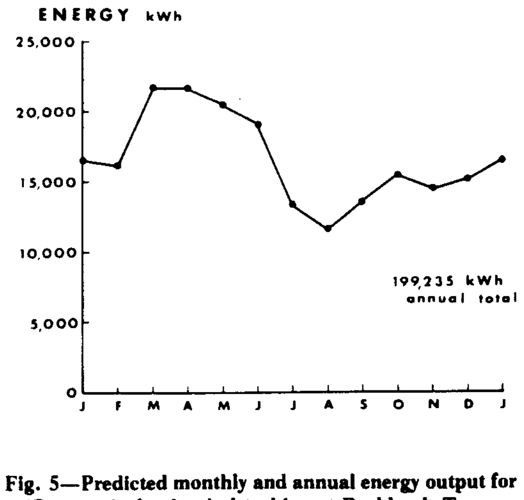

Fig. 5—Predicted monthly and annual energy output for a 17-m vertical-axis wind turbine at Bushland, Texas.

The original 22.5-mm diameter guy cables were replaced by larger 41.3-mm diameter cables to provide a stiffer support system. This new cable system significantly changed the vibratory harmonics of the rotor assembly even though the cable tension was not increased. This guy cable change reduced stress levels in the blades by 25%.

On February 10, 1982, the main contactor in the low-voltage starting system shorted. The contactor was shorted either by lightning or transient voltages due to arcing of power lines during high winds and low humidity. During this failure, the turbine was out of operation for almost 2 months because a new controller had to be assembled and shipped to the site.

The other major component which caused problems was the brakes. Brake systems have caused problems with other wind turbines also. The original brake system consisted of 2 disk brakes mounted on the high-speed shaft between the transmission and generator. These disk brakes have seized due to corrosion, dirt, and other foreign material that restricts movement of the piston. These disk brakes were designed to be operated by a hand or foot lever where variable pressure is applied. When used with a constant pressure system (air tank), the restrictions cause the brakes not to activate or to activate too slowly for proper braking torque. A new brake system was designed and installed on the lower torque tube flange in September 1982. Even though the low-speed brake requires a much larger size and thus cost, it is used because of the potential failure of gears in the transmission (Nellums, personal communication, 1982). This new brake system should provide for a more reliable system, although it has not been fully tested.

Because of these operational problems and others, the turbine has operated considerably less than anticipated. Wind turbines at Bushland should operate at least 5,000 h per year based on windspeed data and other wind turbine operations.

CONCLUSION

A 100-kW vertical-axis wind turbine was installed at Bushland, Texas, to provide electricity for an irrigation system. This unit was an advanced design and should be typical of current production systems. During its initial operation phase, the power and efficiency were better than anticipated; however, several operational problems were encountered. The turbine begins producing power at 5.5 m/s windspeed and reaches its peak at 18 m/s. Rated power of 100 kW is produced at 14 m/s. The unit has obtained a peak efficiency of 43% at a windspeed of 8 m/s, which is 73% of the theoretical maximum. The annual energy output is estimated at 200,000 kWh based on 17 years of Bushland area windspeed data assuming the unit is ready to operate 100% of the year.

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